Optimization of the Image Profile Transform in High Resolution Electrophotography

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Abstract

The resolution of digital electrophotographic printers and copying machines has been steadily increasing and products now exist with 1200 dpi specifications. However, due to the technological difficulties involved in making narrow laser beams, the actual spot size in most applications is much larger than the resolution pitch. For this reason, realizing 1200 dpi image quality is in fact problematic.

For the purpose of constructing a method to resolve the above stated problems, we modeled image profile transforming properties, including the energy distribution of laser beam exposure, the latent image profile, and the profile of developed toner. The resulting image profile is related to such parameters as the exposure condition, PIDC (photo-induced discharge characteristics), which is the potential of the photoreceptor as a function of the exposure energy, and the development curve. Next, we defined the merit function of the target image profile. Employing this function, it was possible to choose the parameters in such a way to produce satisfactory results by using a nonlinear programming method. Finally, we performed experiments using 1200dpi resolution with the parameter values obtained through the optimization process and found that the developed image profile was satisfactorily sharp.

Introduction

Digital electrophotographic machines with 1200 dpi have been popular since 1998. The resolution capability of such machines depends strongly on the laser beam spot size on the photoreceptor, but, as seen in Table 1, this size is not sufficiently small in comparison with the dot pitch.

Table 1. Dot pitch and Estimated Laser beam spot size

Resolution	Dot Pitch Dp	Spot Size Ds	Ds/Dp
300 dpi	84 µm	100-110 µm	1.2-1.3
600 dpi	42 µm	75-85 µm	1.8-2.0
1200 dpi	21 µm	55-65 µm	2.6-3.1

Under the conditions reflected in Table 1, in which the laser beam spot size is far larger than the dot pitch, the laser beam profiles overlap with each other, and the developed image profile turns out to be quite different from the ideal binary pattern.

In this paper, we closely consider the dependence of the developed toner image profile on many parameters and its optimization using automatic design techniques such as lens design. The optimization technique we employ is a non-linear programming method originally proposed by Scharefe[1] in application to the periodic latent image model. In our study, we defined an arbitrary digital exposure pattern, and the calculation for the optimization was performed using a spreadsheet solver package.

The optimized results reveal that it is necessary to use a desaturated region of either the PIDC curve or the development curve to produce the 1200dpi line width as desired.

Modeling Image Profile

Laser Energy Profile of An Arbitrary Exposure Pattern

The laser beam intensity distribution *I*(*x,y*) with power *P*, and beam radius w_x,w_y is expressed by Eq.1, and the energy distribution with scanning speed *v* and duration time Δt is expressed by Eq.2

$$I(x,y) = \frac{2P}{\pi \cdot wx \cdot wy} Exp(-\frac{2x^2}{wx^2} - \frac{2y^2}{wy^2}) \qquad (1)$$

$$\begin{aligned} Ev(x,y) &= \int_0^{\Delta t} I(x - v \cdot t, y) dt \\ &= \frac{2P}{\pi \cdot wx \cdot wy} Exp(-\frac{2y^2}{wy^2}) \int_0^{\Delta t} Exp\left(-\frac{2(x - v \cdot t)^2}{wx^2} \right) dt \end{aligned} \qquad (2)$$

Let us define the exposure state function $G(x_i, y_i)$

$$G(x_i, y_i) = \begin{cases} 1 & \text{laser beam is fired at pixel } (x_i, y_i) \\ 0 & \text{other case} \end{cases} \qquad (3)$$

Then, the total laser energy profile of the exposure pattern $G(x_i, y_i)$ is obtained as follows

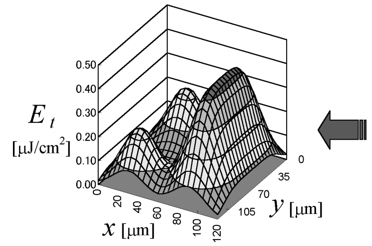
$$E_t(x, y) = \sum_i \sum_j Ev(x - x_i, y - y_j) \cdot G(x_i, y_j) \qquad (4)$$

Potential Voltage Profile of the Latent Image

The potential voltage V_i of the photoreceptor after exposure, expressed as a function of the exposure energy (i.e. the PIDC) is given by

$$V_i = \left(\sqrt{V_O - V_L} - \frac{\sqrt{V_O - V_L} - \sqrt{\dfrac{V_O}{2} - V_L}}{E_h} \cdot E_t \right)^2 + V_L \qquad (5)$$

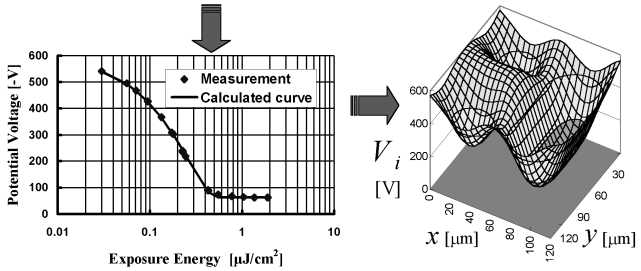
Here, V_o is the potential voltage of the photoreceptor after charging, V_L is the potential voltage after discharge through very high exposure energy (i.e. the saturation voltage) and E_h is the half-decay exposure energy. Figure1 depicts how the exposure pattern is transformed into a latent image profile following Eqs.1-5.



		0	1	2	3	4	5	6
	yi \ xi	0	20	40	60	80	100	120
0	0	0	0	0	0	0	0	0
1	20	0	1	0	0	1	0	0
2	40	0	0	0	0	1	0	0
3	60	0	0	0	0	1	0	0
4	80	0	0	0	0	1	0	0
5	100	0	1	0	0	1	0	0
6	120	0	0	0	0	0	0	0

2. Laser Energy profile *Et*

1. Exposure Pattern *G*(*x*,*y*)



3. PIDC curve

4. Latent image profile $V_i(x,y)$

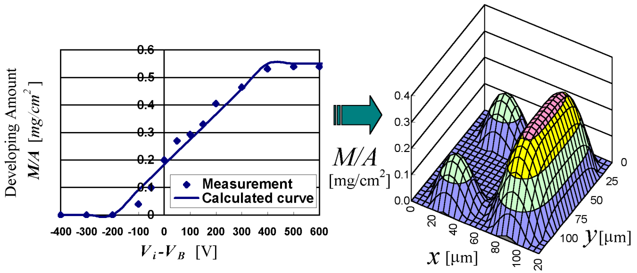
Figure 1. Exposure pattern G(x,y) , its energy profile E_t, the PIDC and the latent image profile.

Developed Image Profile

After the latent image profile $V_i(x,y)$ is produced as described above, it is then converted into the developed image profile. The developing amount per unit area, M/A (where M is the mass of toner), is described as

$$M/A = \begin{cases} 0 & \text{if } V_i < V_{th} \\ -\dfrac{W_m \cdot V_{th}}{W_m - V_{th}} + \dfrac{W_m}{V_m - V_{th}} \cdot (V_i - V_B) & \text{if } V_{th} \le V_i \le V_m \\ Wm & \text{if } V_i > V_m \end{cases} \qquad (6)$$

where V_{th} is the voltage at the beginning of development, V_m is the voltage at the end of development, W_m is the final developed amount, and the V_B is the bias potential on the development roller. The resultant developed image profile is displayed in Figure 2.



5. Development curve

6. Developed image profile

Figure2. Development curve and developed image profile

Since V_{th}, V_w and W_m are functions of the toner charge-to-mass ratio Q/M, the toner mass per unit area on the development roller, and so on, the development curve can be controlled by adjusting these parameters.[2,3] Equation 6 indicates that a development curve is linear, but in some cases where a large distribution of toner diameters or toner charges exist, it becomes non-linear. In these cases, it is better to use experimental data and the interpolation curve obtained from them in order to more accurately derive a developed image profile.

Image Profile Optimization

Geometry of Beam Size and Dot Size

Clearly, if Ds/Dp becomes larger, the width of one line, W_1, becomes larger, and as a result the ratio of two-line width W_2 to the one-line width W_1 becomes smaller than 2 although it should originally be 2. This situation is depicted in Figure 3.

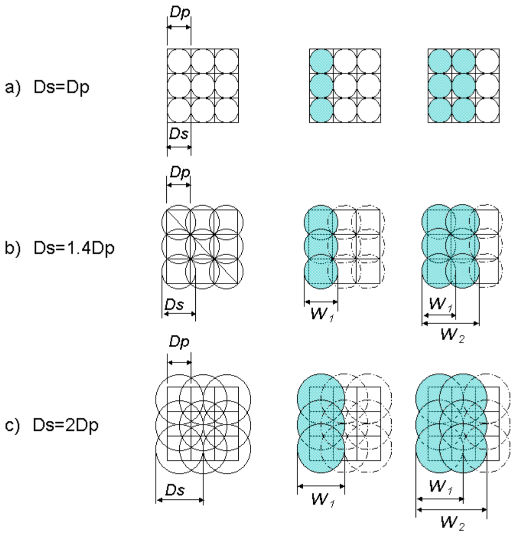


Figure 3. Beam size Ds and dot pitch Dp. W_2/W_1 is ideally 2

The Value of Ds/Dp and the Exposure Energy Profile

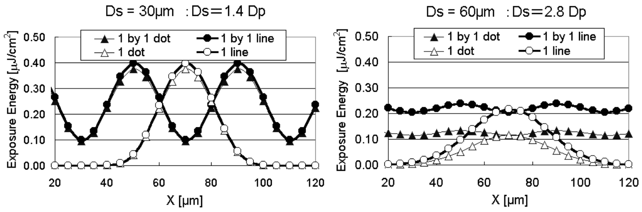


Figure 4. Energy profiles of several patterns

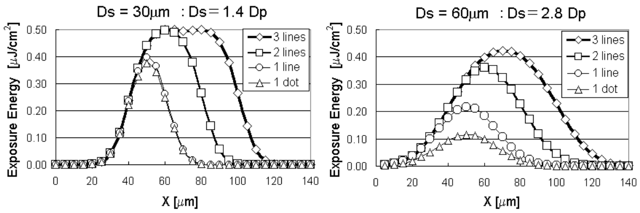


Figure 5. The growth of energy profiles of line images

Figure 4 illustrates how the exposure energy profiles of several image patterns change as Ds/Dp becomes larger. When Ds/Dp is smaller than 1.4, the cross talk between adjacent dots is small enough for each pattern to be resolved, but when Ds/Dp reaches 2.8, only single dot or single line patterns can be resolved.

Figure 5 shows how the energy profiles of line patterns grow as Ds/Dp increases. From this figure we can see that the cross talk results in both a broadening of the energy distribution and a change in the amplitude of the energy profile.

Optimization of Developed Line Width at 1200 Dpi

In laser scanning optics, it is difficult to make the laser beam width smaller than 30μm unless we use a blue laser. This can be understood on the fact that the limit of resolution of a Gaussian laser beam, δ, is given by

$$\delta = \frac{2\lambda}{\pi \cdot NA} \tag{7}$$

which corresponds to the case in which there is no aberration in the focusing lens. Our goal is to produce 1200 dpi line patterns with a beam size of 60μm, where Ds/Dp is 2.8. In this situation, it is important to control the image profile distribution and the amplitude, as described above.

Let us suppose that f_1 is the developed image profile of one line and f_2 is that of two lines, which is identical to one line at 600 dpi. We define that the line width to be the width over which the developed amount is greater than 0.4 mg/cm². The optimization problem is formulated as follows

Minimize $|W_2-2W_1|$
with respect to P, E_h, V_B,….
subject to

$f_1(x_{1S}) = f_1(x_{1E}) = 0.4$ mg/cm²
$f_2(x_{2S}) = f_2(x_{2E}) = 0.4$ mg/cm²
$W_2 = x_{1E} - x_{1S} < 60$ μm
$W_1 = x_{2E} - x_{2S} < 30$ μm
$1.8 < W_2/W_1 < 2.2$

We used Microsoft Excel's NLP (Nonlinear Programming) solver to solve this optimization problem. The design parameters are listed in Table 2.

Table 2. Design parameters and representative values

Exposure	Symbol	Value
Laser power	P	Variable
Laser beam radius	w_x, w_y	30 μm
Pulse width	Δt	17.76 nsec
Scanning speed	v	1192 m/sec
Photoreceptor		
Surface potential	V_S	Variable
Light voltage	V_L	-60 V
Half decay exposure energy	E_h	Variable
Development		
Voltage threshold	V_{th}	-100 V
Voltage end	V_m	200 V
Developed mass at V_m	W_m	0.6 mg/cm²
Bias potential on roller	V_B	Variable

Table 3. Optimized results

Parameters		Initial Value	Optimal Value
P	mW	0.15	0.1
V_s	V	-600	-800
E_h	μJ/cm²	0.1	0.1
V_B	V	-400	-350
W_1	μm	50	26
W_2	μm	72	52
Experimental result		W_2/W_1 =100/65 = 1.53	W_2/W_1 =64/32 = 2

An example of the optimized results is given in Table 3. Excel has two NLP algorithms, a quasi-Newton method and a conjugate-gradient method. We used the Quasi-Newton method. About ten to twenty iterations were needed to obtain the solution.

We examined how the calculated parameter values work in real processes. In experiments, we used a mono-component non-magnetic development system. The toner charge-to-mass ratio Q/M was set to 30μC/g so that the development curve corresponds to the designed values given in Table 2. The developed line widths so obtained were larger than the calculated ones, but W_2/W_1 was found to be 2.0.

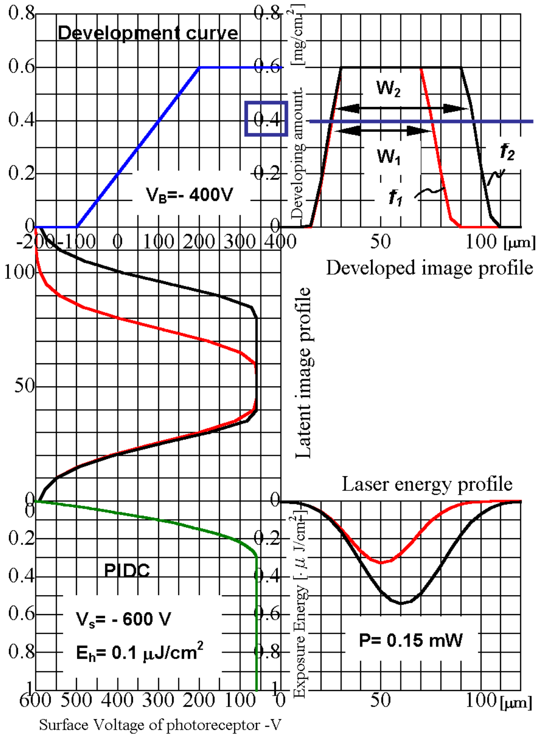


Figure 6. Image profile before optimization

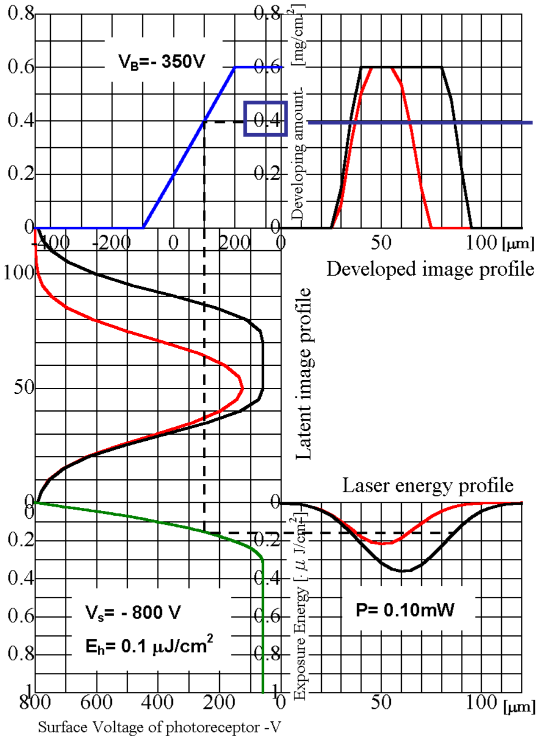


Figure 7. Image profile after optimization

Figure 7, in comparison with Figure 6, shows how the image profile is transformed so that the W_2/W_1 becomes 2.0. The optimal result reveals that it is necessary to use a desaturated region of the PIDC curve in order to keep the profile distribution sufficiently narrow.

Discussion

Figure 7 indicates that we used a desaturated region of the PIDC curve. We found this necessary to obtain the optimal image sharpness at 1200 dpi. In other words, it is necessary to underexpose in order to achieve a sufficiently narrow line width of the developed image. It is also possible to obtain the desired result by using a desatureted region of the development curve. This can be achieved by adjusting the developing bias V_B.

For further optimization, tolerance analysis is needed to examine the robustness of the process. We believe that proper application of the potential control technique and insuring stable toner charging are the key to maintaining the proper image profile.

In order to calculate the latent image profile more accurately, the carrier diffusion inside the photoreceptor and the response of the spatial frequency (i.e. MTF) should be considered. However, when Ds/Dp is larger than 2, laser beam cross talk is dominant, and the latent image profile is approximately obtained by using the PIDC curve.

Conclusion

1. We constructed an analytical model of an image profile transform through digital exposure to development. The profile optimization for high-resolution image reproduction was carried out using the NLP method, which enabled us to obtain line widths of 1200 dpi images with sufficient narrowness.
2. When Ds/Dp comes close to 3, it is necessary to use a desaturated region of either the PIDC curve or the development curve in order to obtain a profile distribution that is sufficiently narrow.

References

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Biography

Tetsuro Toyoshima received his B.S. and M.S. degree from Kyoto University in precision engineering in 1983 and 1985, respectively. After graduation, he joined the Sharp Corporation in 1985. He belongs to Production Technology Laboratories. His current research interests include optical design, latent image forming, and electrophotographic development technology. He is a member of the Imaging Society of Japan.